

RIP



A FREE

NEUTRON

BORN JULY 15, 2016  
DIED 10 MINUTES LATER



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# THE LIVES & TIMES *of* NEUTRONS

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*Most neutrons inside atoms are stable. But get one on its own,  
and it will disintegrate in about ten minutes.*

THERE ARE ONLY THREE subatomic particles that make up everyday objects, and one of them is unstable. The neutron, while stable enough when found inside an atom's nucleus alongside protons, disintegrates after about ten minutes on its own. But therein lies the rub—*about* ten minutes—because the neutron has been surprisingly reluctant to give up the exact number.

Radioactive decay, such as the one that enacts the death of a neutron, happens as a function of chance, making it impossible to know how long any particular neutron will live. However, scientists can characterize the half-life for a population of neutrons—how long it takes for half the neutrons to decay—and, in principle, do so with great precision. Experimental physicists have worked diligently to that end, broadly succeeding and improving the precision of neutron half-life measurements by more than a factor of ten in recent decades. But they have hit a snag. Increasingly high-tech measurements, with ever-smaller uncertainties, are converging to not one but *two* different answers.

Some experiments gather neutrons and count how many remain after an elapsed time. Other experiments count the particles left behind when neutrons decay. Both are expertly done, but their results do not jibe with one another, leaving two possibilities. Either the experiments are wrong somehow or the neutron itself is more complex than anyone thought. At Los Alamos National Laboratory, a bold new variation on the neutron-counting experiment aims to resolve this dilemma.

## Ubiquitous but elusive

James Chadwick, credited for the 1932 discovery of the neutron, and Ernest Rutherford, Chadwick's mentor who was himself renowned for discovering the atomic nucleus, initially conceived of the neutron not so much as a distinct subatomic particle, but rather as a close arrangement of electron and proton: the negative particle hovering near and canceling out the positive one. This turned out to be wrong; the neutron is its own entity. But the conception of the neutron as a proton-electron blend was still valid in a sense, because when neutrons decay, two of the three particles that emerge are in fact proton and electron. (The third is the antiparticle to the uncharged and almost massless neutrino.)

This neutron-disintegration process, known as beta decay, also occurs in neutron-rich isotopes of various elements. An energetic electron and antineutrino speed out of the nucleus, and a proton remains in the former neutron's place. The resulting atom, now with one more positive charge in its nucleus, advances one position up the periodic table. That's if the atom is in some sense overloaded with neutrons to begin with. Conversely, if an atom is "satisfied" with its relative number of protons and neutrons, then its neutrons apparently never decay. For example, the isotope iron-58, with 26 protons and 32 neutrons, appears perfectly stable. But iron-59, with 26 protons and 33 neutrons, undergoes beta decay. Moreover, how long neutrons survive inside a nucleus before decaying similarly depends on the nucleus in question. Iron-59 has a half-life of more than six weeks, while iron-63, with four more neutrons, lasts only six seconds. But for a free neutron, unattached to any atom, it's always about ten minutes.

Officially, the neutron half-life is quoted at  $611.0 \pm 1.0$  seconds. This level of precision is not atypical among particle-physics lifetimes, but it is far from the best. The lifetime of the muon, for example—a difficult-to-detect, heavier cousin to the electron that can only exist for a millionth of a second—is known to within a trillionth of a second. And most of the other lifetimes known with comparable precision to that of the

So-called bottle experiments disagree. In a bottle experiment, neutrons are confined in a container. Then, after waiting for different amounts of time, they are counted to see how many neutrons remain. But unlike working with charged protons, both confining and counting are difficult with neutrons. Because of their lack of electrical charge with which to interact with other particles, neutrons are generally able to

penetrate into (or even through) solid matter, including the walls of the bottle and the detector material.

Here again, as with counting neutrons in beam experiments, experimenters have devised a workable solution: they chill the neutrons down to ultracold temperatures. Then, instead of zipping about at rapid particle-physics

speeds and plunging into the walls of the bottle, the neutrons drift about very slowly, gingerly bouncing off its walls. Some neutrons might get out, but their loss rate can be adjusted—for example, by varying the temperature—and then extrapolated to a loss-free condition. Detector losses can be accounted for in a similar fashion, and 25 years of bottle experiments average out to  $609.7 \pm 0.4$  seconds for the neutron half-life.

### Bigger, better bottle

At Los Alamos, working with neutrons is practically a way of life. The work is never easy, and Los Alamos scientists have learned how to live with that. To resolve the measurement discrepancy between beams and bottles, someone has to get in there and ferret out any possible source of systematic uncertainty. In a bottle experiment, for example, any neutron that escapes without being properly accounted for in the calculations will make experimenters think it decayed, causing them to underestimate the neutron survival rate. Any misunderstanding of the sensitivity of the neutron detector will similarly skew the results.

“I think a lot of us in the physics community secretly trust the beam results, and we’ve been expecting to uncover a flaw in the design of previous bottle experiments,” says Susan Seestrom. Seestrom is a Los Alamos physicist who came out of retirement specifically to search for that flaw. She had been promoted up the chain to manage the experimental physics directorate during her official Los Alamos career and ultimately chose to both retire and un-retire to get back to doing the science that most inspires her—solving one of the world’s great experimental-physics mysteries.

“The only way to find out why beam and bottle experiments disagree with one another so systematically,” says Seestrom, “is to adjust or improve upon one of them and then see if the changes make a difference.” Together with Los Alamos colleagues, postdoctoral scientists, students, and external collaborators (at Indiana University, North Carolina State University, Tennessee Technological University, and elsewhere), Seestrom is working to improve a special kind of magnetic bottle for neutrons. While uncharged, neutrons are faintly

## BEAM AND BOTTLE EXPERIMENTS ARE STRIKINGLY INCOMPATIBLE WITH ONE ANOTHER, DIFFERING BY NEARLY SIX SECONDS.

neutron apply to particles that are never observed in nature and can only be made to appear for a minuscule fraction of a second in the laboratory.

Yet even the comparatively lumbering one-second precision for the neutron lifetime may be overstated because of the pronounced discrepancy between the two major categories of neutron-lifetime experiment. Each produces self-consistent results to within about one second as advertised, but measurements from experiments in one category are strikingly incompatible with those from the other, differing by nearly six seconds—and this for the lifetime of a particle that children learn about in middle school, one of only three that comprise all the objects in the world.

### Of beams and bottles

In one type of experiment, a beam of neutrons is launched through an arrangement of electric and magnetic fields that separate out the positively charged protons produced when neutrons undergo beta decay. The remaining neutrons, being uncharged, continue on, but protons accumulate and are subsequently diverted into a detector. Both the capturing and the detection of charged protons are less error-prone than comparable processes for uncharged neutrons.

In theory, one can simply compare the proton count with the number of neutrons in the beam to obtain the information needed to calculate the neutron lifetime. Figuring out how many neutrons were in the beam to begin with is trickier than counting the protons, but experimenters have devised a clever way to circumvent that problem. They use a lithium-based neutron detector for which the detection rate is known to depend upon the neutrons’ speeds in exactly the same way that the number of neutrons passing through the proton-collection segment of the beam does. In this way, the uncertainty in the number of neutrons that go undetected by the lithium detector cancels out of the math entirely.

The upshot is this: beam experiments ought to calculate the neutron half-life quite reliably. An average of beam-experiment measurements over the last 25 years or so gives a neutron half-life of  $615.5 \pm 1.5$  seconds.

magnetic, and because magnetic walls have different confinement properties than material walls, that difference could help scientists identify the source of the measurement discrepancy.

The magnetic walls are constructed from about 6000 powerful permanent magnets, each 1-inch square by 2 inches long, glued together in a pattern of rotating orientations to make what's called a Halbach array. It is designed to produce a consistent magnetic field—20,000 times stronger than the earth's magnetic field—everywhere along the bottle's surface. At

thereby escaping the cleaning process.

The whole setup, designed at Los Alamos, is undeniably a marvel of science and engineering. But Steven Clayton, one of Seestrom's colleagues on the project, notes that its improvements over conventional bottle experiments come with a cost.

"I'm confident that magnetic containment is the way to go because it's impossible to know the exact surface properties of even the smoothest of physical walls," says Clayton.

## IT'S THE MOST HIGHLY INSTRUMENTED NEUTRON-LIFETIME EXPERIMENT EVER DONE.

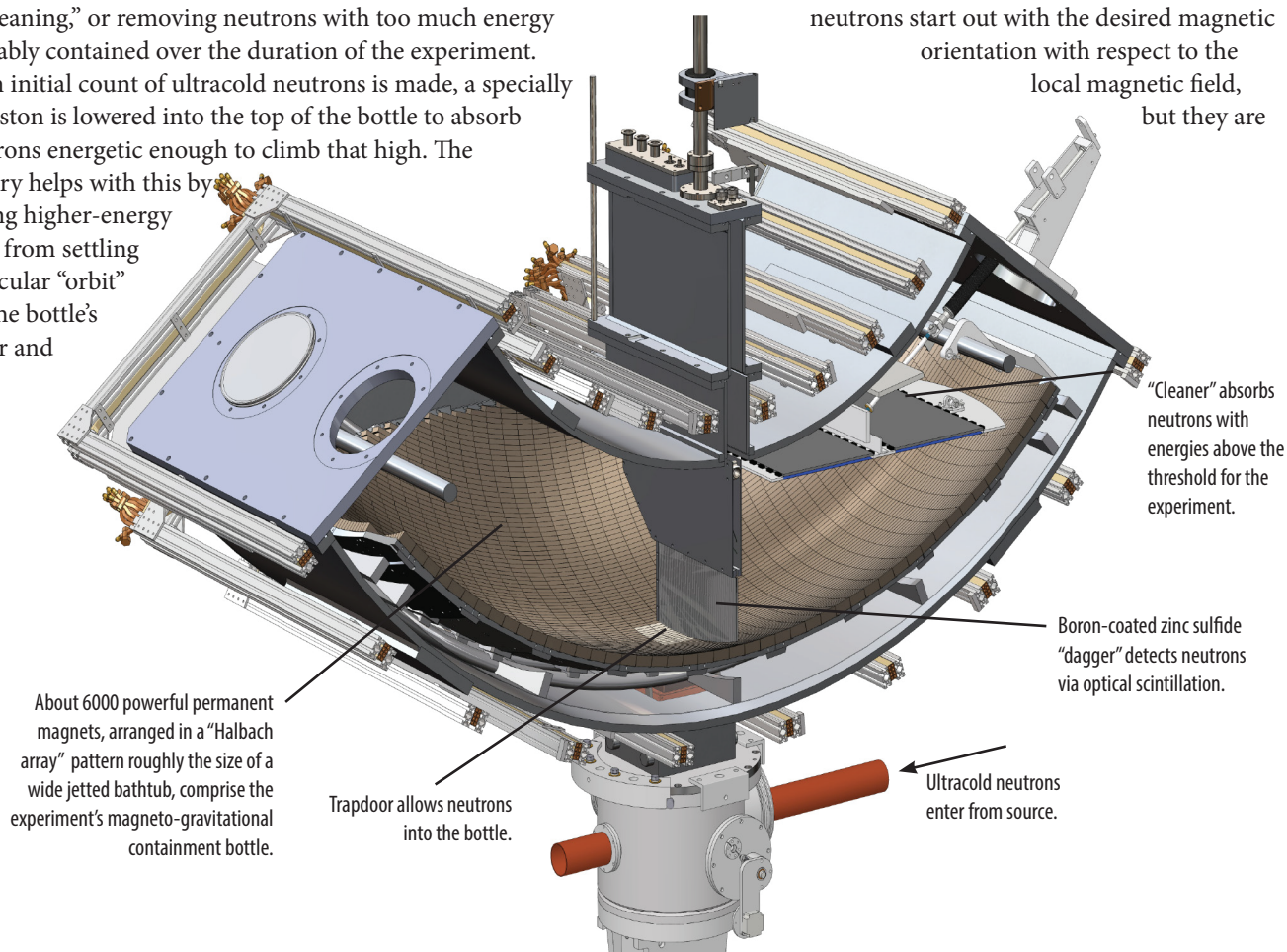
the bottom of the array is a trapdoor through which ultracold neutrons enter to start the experiment.

The magnetic bottle doesn't look much like a bottle, however; it looks more like a broad, slightly lopsided, metallic bathtub. Its top is open, both to allow instrumentation to be lowered in and because gravity is sufficient to keep the ultracold (that is, ultralow energy) neutrons from climbing out. Its bottom (magnetic) surface is somewhat asymmetrical, shaped like an egg sliced in half along its length, to help with a process called "cleaning," or removing neutrons with too much energy to be reliably contained over the duration of the experiment. Before an initial count of ultracold neutrons is made, a specially coated piston is lowered into the top of the bottle to absorb any neutrons energetic enough to climb that high. The asymmetry helps with this by preventing higher-energy neutrons from settling into a circular "orbit" around the bottle's perimeter and

"But switching to magnetic walls doesn't simply eliminate the uncertainties of physical walls the way you would want it to. It replaces them with different uncertainties that we have to understand and control."

In particular, magnetic containment only works if the neutrons' internal magnetism is pointing the right direction. Otherwise, the magnetic field would pull them into the bottle's walls, making it appear that they had been lost to beta decay, rather than reflect them back into the bottle's interior. The

neutrons start out with the desired magnetic orientation with respect to the local magnetic field, but they are



The Los Alamos magnetic-bottle experiment is poised to resolve the present ambiguity in the measured half-life of the neutron. Unlike previous bottle-type experiments, it combines magnetic neutron containment (instead of solid walls), a comparatively large volume (for better data statistics), an asymmetric shape (to drive out unwanted high-energy neutrons), real-time visual neutron detection inside the primary container (to minimize detection uncertainties), and blinded data processing (to eliminate human bias).



vulnerable to reversals in magnetic orientation if they move through either a steep gradient or a gap in the surrounding magnetic field. Detailed calculations show that gradients steep enough to affect the experiment shouldn't pose a problem, and an additional applied magnetic field ought to eliminate any gaps. Clayton will need to perform a comprehensive magnetic-field mapping inside the bottle to be certain, but indications to date suggest that magnetic reversals are unlikely to affect the results.

After running down such sources of uncertainty, all that remains is to count the neutrons. Comparing two measurements—one soon after filling the bottle and another more than two half-lives later—reveals the timescale for beta decay and, therefore, the lifetime of the neutron.

### Boron-battered blade

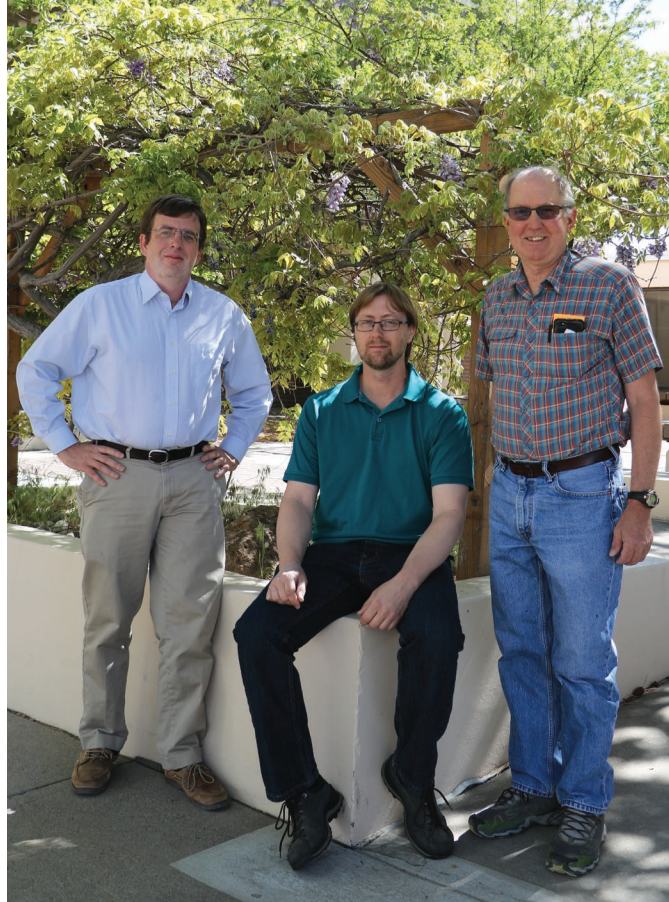
“Even the easy stuff—like *counting*—is unbelievably difficult when it comes to experimental physics at a precision below 0.1 percent,” says Chris Morris, a Los Alamos nuclear physicist. Initially, the plan was to open the trapdoor at the bottom of the bottle and let the neutrons drain out to be counted. It may sound simple, but just as walls and magnetic fields come with their own complications, so too does draining the neutrons.

“If how long the neutrons have been in the bottle affects the way they're sloshing around when the trapdoor is opened, we'll get biased counts and biased results,” Morris explains. “So we came up with a better way. And after that, we came up with an even better way.”

First, Morris and the team developed a different mechanism for counting neutrons without draining them from the bottle, making their counts directly inside the bottle instead. They created a rigid “dagger” coated on both sides with the isotope vanadium-51. (The term refers to the retractable daggerboard some sailboats employ as a keel for stability.) When lowered into the bottle, the dagger would absorb neutrons, thereby converting its vanadium-51 into vanadium-52, which is radioactive with a 3.7-minute half-life. Then all the scientists had to do was count the subsequent vanadium decays with radiation detectors—and of course work out the backgrounds and efficiencies of those detectors. The problem was, how many 3.7-minute time periods could they afford to wait?

“It worked, and we got good data, but it was taking too long,” recalls Morris. “We only get so much time with the ultracold neutron source, and increasing the precision of our results means conducting experiments in rapid succession for better counting statistics and better understanding of systematic errors. We couldn't very well do that if we had to wait around for all the vanadium to decay each time.”

Help ultimately came from the Lab's chemistry division, where researchers had independently developed a technique for depositing a nanometer-scale coating of a different neutron absorber, boron-10, onto a zinc-sulfide surface. When a neutron strikes boron-10, an alpha particle (helium nucleus) is emitted, causing the zinc sulfide—a scintillator material used



Left to right: Andy Saunders, Steven Clayton, and Chris Morris, with upwards of ten thousand trillion trillion neutrons in each of their bodies. Fortunately, these neutrons are not free, but rather locked up inside atomic nuclei and therefore, by and large, in no danger of decaying.

by experimental physicists for about 100 years—to glow. This happens instantly, so there's no half-life to wait out. And it happens visually, so a specialized camera focused on the dagger, even from some distance away, could track all the neutron impacts in real time. Because of this, there would no longer be any ambiguity about whether the neutrons were sloshing around differently from one measurement to the next. Such effects could be directly observed and mathematically taken into account.

### Matter Particle Life Expectancy



Half-life  
at least  $10^{29}$  years



Half-life  
at least  $10^{28}$  years



Half-life  
10.2 minutes

As far as anyone knows, the proton and electron could be perfectly stable, never undergoing radioactive decay. At the very least, they are extremely long-lived, with minimum known lifetimes enormously in excess of the 14-billion-year age of the universe. Among the three primary matter particles, only the neutron is unstable. Had the primordial neutrons produced in the big bang not found their way to safety inside atomic nuclei before a few of their half-lives had expired, no elements beyond hydrogen would have been produced. As Los Alamos's Susan Seestrom says, while gesturing at trees, buildings, and other people, “none of this would be here.”

There's still much work to be done to optimize the system—the ideal size and shape of the dagger, the ideal camera setup, some lingering aspects of the higher-energy neutron cleaning process, and so on. But it is now clear that the experiment will work to measure the neutron half-life without the same uncertainties present in previous bottle experiments.

“Our prototype worked the first time,” proclaims a visibly incredulous Clayton. “This is the most highly instrumented neutron-lifetime experiment ever done, and we're actually ahead of ourselves.”

### The expectations game

The researchers aim to iron out the details of the experiment and obtain results in two phases. Over the next year, they intend to obtain a neutron half-life measurement

## IN EXPERIMENTAL PHYSICS, EVEN THE EASY STUFF—LIKE *COUNTING*—CAN BE UNBELIEVABLY DIFFICULT.

with 1-second uncertainty. This will put them on par with the best existing measurements and in the range of obtaining data that could affect scientists' understanding of particle physics overall. Then in the following years, they expect to further develop techniques to drive those uncertainties down to 0.2 seconds, at which point they will be able to advance human understanding of physics and, to some extent, help explain what went on at the birth of our universe.

When the universe was just a few seconds old and still very hot, particle interactions produced equal numbers of protons and neutrons, which could merge into nuclei of various isotopes of hydrogen, helium, and lithium. As the universe expanded and cooled, neutrons began to decay, and protons became relatively more numerous. But exactly how much more numerous? That depends on the neutron lifetime and strongly affects how much of each nucleus was able to form. Observational measurements of these abundances in the universe today provide a sensitive probe of the dynamics of the big bang—currently limited by our knowledge of the neutron lifetime.

“Grand though they may sound, and as important as they are, advancing particle physics and the big bang theory with better-precision measurements may not ultimately be the primary prize of this work,” says collaboration spokesperson Andy Saunders. “They might even be considered a sort of consolation prize.” Many leading physicists are expecting the results to defy previous bottle-type experiments, helping to point out where those experiments went wrong and thereby bringing bottle measurements in line, so to speak, with beam-experiment measurements. This would be success: resolving a longstanding physics dilemma. But the alternative, not resolving the dilemma, might in some sense be even better.

If the Los Alamos experiment supports other bottle experiments and continues to defy beam experiments, it could suggest new and unexpected physics. After all, bottle experiments count the number of neutrons remaining, while beam experiments count the number of protons created by neutrons undergoing beta decay. If neutrons decay or otherwise disappear by some other process, in addition to beta decay, that would explain why the beam experiments come up with longer neutron lifetimes: they're only counting one of the ways neutrons die. In other words, it could mean that both kinds of experiments are correct, but only bottle experiments measure the neutron's overall lifetime. Beam experiments measure its beta-decay lifetime.

Thus, if the bottle-beam discrepancy holds up, it would mean the discovery of an entirely new physical process.

A discovery like that doesn't come along every day, and there's no telling what future scientific and technological advances it might ultimately generate. So what's it going to be, spokesperson Saunders? Do

your preliminary results point toward resolving the bottle-beam dilemma, or do they point to something potentially bigger?

“We don't have results to share using the boron dagger system yet, and those will be the ones to watch,” Saunders says. “But our previous-generation experiment with the vanadium dagger yielded a neutron half-life of  $609.5 \pm 2.9$  seconds, smack-dab in the middle of the nonmagnetic bottle-experiment range. Even with the fairly large uncertainty, that's distinctly outside of the beam-experiment range.

“Now, we didn't pursue tighter uncertainties with this result because we had already moved on to the boron-blade detector,” Saunders continues. “But if it holds up, it will either imply a flaw in the beam experiments or the discovery of new physics.” New physics from a particle we've known since 1932—either that, or the experiment will lay to rest a major unresolved issue in physics, as planned. **LRD**

—Craig Tyler

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